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Effects of dietary arginine supplementation during gestation and lactation on the performance of lactating primiparous sows and nursing piglets¹

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ABSTRACT: A 2 × 2 factorial arrangement of treatments in a randomized block design was used to determine the effects of dietary Arg supplementation during gestation and lactation on the lactation performance of 38 first-parity sows. At 30 d of gestation, pregnant gilts were allotted based on BW to 1 of 2 diets supplemented with 1% L-Arg·HCl or 1.7% L-Ala (isonitrogenous control). After farrowing, sows were further allotted based on BW within previous gestation treatment groups to 1 of 2 lactation diets supplemented with 1% L-Arg·HCl or 1.7% L-Ala (isonitrogenous control). All gestation diets contained 3.1 Mcal/kg and 12.2% CP (as is) and were fed 2 kg/d in 2 equally sized meals, whereas all lactation diets contained 3.2 Mcal/kg and 18.6% CP (as is) and were fed ad libitum. Litter size was standardized to 10 piglets by cross-fostering within 24 h postfarrowing. On a weekly basis, BW and backfat (BF) thickness of sows, as well as piglet BW were measured, and

blood and milk samples were obtained from the sows. Number of days from weaning to estrus and ADFI were also recorded. There were no differences in BW, BF thickness, ADFI, or days until return to estrus among treatment groups. There was no effect of the gestation diet or a gestation × lactation diet interaction on any parameter measured. On d 7 of lactation, plasma concentrations of Arg and insulin in sows, as well as concentrations of most AA in milk, were greater ($P < 0.05$) in response to Arg supplementation during lactation compared with the control. Weight gain of piglets from sows fed the Arg-supplemented diet during lactation was greater between d 0 and 7 ($P < 0.01$) and between d 0 and 21 ($P < 0.05$) of lactation compared with piglets from sows fed the control diet. Collectively, results from this study indicate the potential beneficial effects of dietary Arg supplementation in improving the lactation performance of first-parity sows.

Key words: L-arginine, lactation performance, litter weight gain, sow

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INTRODUCTION

Young animals have a high requirement for Arg (Southern and Baker, 1983; Fickler et al., 1994) because of the utilization of Arg by multiple metabolic pathways (Wu and Morris, 1998; Li et al., 2007). However, Arg intake from sow's milk is low relative to the need for protein deposition in piglets (Davis et al., 1994; Wu and Knabe, 1994; Kim et al., 2007). Estimates based on the supply of Arg from sow's milk and the Arg requirement of piglets revealed that sow's milk provides less than

40% of the daily requirement in 7-d-old suckling pigs (Wu et al., 2004). Both metabolic and growth data indicate that an Arg deficiency is a major factor limiting maximal weight gain of milk-fed piglets (Kim and Wu, 2004; Wu et al., 2004; Frank et al., 2007).

Increasing milk Arg intake by suckling piglets could be an effective means of enhancing their growth. In addition to the feed intake of sows and the suckling intensity of piglets, milk production is also influenced by the angiogenesis of mammary tissue and blood flow to mammary glands, which enhance nutrient delivery to the mammary gland for milk synthesis (Trottier et al., 1997). Mammary blood flow and angiogenesis are regulated by Arg-derived nitric oxide (Meininger and Wu, 2002; Lacasse and Prosser, 2003). Furthermore, milk production is highly correlated with mammary gland growth (Ceriani, 1974; Kim et al., 2000) and Arg is required for optimal mammary gland growth (Pau

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and Milner, 1982). At a high dosage, Arg stimulates the secretion of prolactin and growth hormone, which are necessary for mammary development (Knopf et al., 1968; Davis, 1972).

We hypothesized that supplementing Arg to the diets of first-parity sows during gestation and lactation might stimulate the weight gain of sow-reared piglets, possibly by increasing nutrient utilization, and therefore increasing milk production and altering nutrient composition in milk.

MATERIALS AND METHODS

Animals, Experimental Diets, and Design

The animal care and use protocol was approved by the Animal Care and Use Committee of Texas Tech University. A 2×2 factorial study was conducted to determine the effects of L-Arg supplementation in gestation in combination with lactation diets on the lactation performance of 38 first-parity sows (Camborough 22, Pig Improvement Co., Franklyn, KY).

At d 30 of gestation, pregnant gilts with an average BW of 166.3 ± 1.8 kg and BF thickness of 13.3 ± 0.2 mm were housed in individual gestation crates (2.1×0.6 m), and gilts with similar BW were paired and then randomly allotted to 2 dietary treatments, which consisted of corn- and soybean meal-based diets supplemented with either 1% L-Arg-HCl or 1.7% L-Ala (isonitrogenous control, Ajinomoto, Tokyo, Japan; Table 1). At 110 d of gestation, pregnant gilts were transferred to individual farrowing crates (1.5×2.2 m). Within 24 h postfarrowing, sows in each treatment group were assigned randomly to corn- and soybean meal-based lactation diets supplemented with either 1% L-Arg-HCl or 1.7% L-Ala (isonitrogenous control; Table 1). Litter size was standardized to 10 piglets, depending on their availability, by cross-fostering within 24 h postfarrowing. The number of piglets per sow ranged from 9 to 13 piglets but was equalized within BW groups (blocks). Alanine was chosen for the isonitrogenous control because Ala is not toxic and is not a substrate for Arg synthesis, but is extensively catabolized by pigs (Kim and Wu, 2004; Kohli et al., 2004). Furthermore, previous studies have shown no differences in reproductive performance between first-parity sows provided either conventional diets or diets supplemented with 1% Ala (Ji, 2004; Mateo et al., 2007). The supplemental level of 1% L-Arg-HCl was chosen because it was shown in our previous study to increase plasma concentration of Arg in pregnant pigs by 65% at 2 h after feeding. This indicated that Arg provided through dietary supplementation can be delivered to the body successfully for further metabolism (Wu et al., 2007).

Gestation diets contained 3.1 Mcal/kg and 12.2% CP, and lactation diets contained 3.2 Mcal of ME/kg and 18.7% CP (as is). These diets were designed to meet or exceed the nutrient requirements for both gestating and lactating sows set forth by the NRC (1998). Gestat-

Table 1. Composition of gestation and lactation diets, as-fed basis

Item	Experimental diet, ¹ %			
	Gestation		Lactation	
	Control	Arg	Control	Arg
Ingredient				
Corn grain	71.20	71.20	57.50	57.50
Soybean meal, 44% CP	10.50	10.50	27.00	27.00
Alfalfa meal, 17% CP	5.00	5.00	—	—
Molasses cane	4.30	5.00	2.95	3.65
Potassium chloride	0.75	0.75	0.10	0.10
Salt	0.35	0.35	0.35	0.35
Vitamin-mineral premix ²	3.00	3.00	3.00	3.00
Vegetable oil	0.50	0.50	3.00	3.00
Dicalcium phosphate	2.20	2.20	2.50	2.50
Limestone	0.50	0.50	0.70	0.70
L-ARG-HCl	—	1.00	—	1.00
L-Ala	1.70	—	1.70	—
Chemical composition				
DM, %	89.3	89.3	90.0	90.0
ME, Mcal/kg	3.1	3.1	3.3	3.3
CP, %	12.2	12.2	18.7	18.7
Lys, %	0.56	0.56	0.96	0.96
Met + Cys, %	0.44	0.44	0.59	0.59
Try, %	0.13	0.13	0.21	0.21
Thr, %	0.45	0.45	0.67	0.67
Ca, %	0.94	0.94	1.04	1.04
Available P, %	0.47	0.47	0.54	0.54
Total P, %	0.69	0.69	0.79	0.79

¹Gestation diets were provided at 2 kg/d in 2 meals (0700 and 1800 h); lactation diets were provided ad libitum from farrowing to 21 d of lactation. Control diets were made isonitrogenous with the addition of L-Ala at 1.7% at the expense of molasses cane, and Arg diets were made isonitrogenous with added L-Arg-HCl at 1% at the expense of molasses cane. (Supplemental AA were obtained from Ajinomoto Co. Inc., Tokyo, Japan.) Analyzed CP (as-fed basis) content of the diets was as follows: 12.5% for the Arg-supplemented gestation diet; 12.4% for the control gestation diet; 18.5% for the Arg-supplemented lactation diet; and 18.9% for the control lactation diet.

²The vitamin premix provided the following per kilogram of complete diet: 46.7 mg of Mn as manganous oxide; 75 mg of Fe as iron sulfate; 103.8 mg of Zn as zinc oxide; 9.5 mg of Cu as copper sulfate; 0.72 mg of I as ethylenediamine dihydroiodide; 0.23 mg of Se as sodium selenite; 7,556 IU of vitamin A as vitamin A acetate; 825 IU of vitamin D₃; 61.9 IU of vitamin E; 4.4 IU of vitamin K as menadiolone sodium bisulfate; 54.9 µg of vitamin B₁₂; 13.7 mg of riboflavin; 43.9 mg of D-pantothenic acid as calcium pantothenate; 54.9 mg of niacin; and 1,650 mg of choline as choline chloride.

tion diets (2 kg/d) were fed twice daily at 0700 and 1800 h between d 30 of gestation and farrowing. Lactation diets were provided to sows ad libitum throughout the lactation period. Water was available ad libitum during the gestation and lactation periods. The farrowing room temperature was maintained at 25°C, with supplemental heat for piglets provided by heat lamps. During the entire 21-d lactation period, feed disappearance of the sows was recorded and the piglets had no access to creep feed. Body weight of the sows was obtained within 24 h postfarrowing and on d 7, 14, and 21 of lactation. Backfat thickness of sows was measured by ultrasound (Keiki LS-1000, Tokimec Inc., Tokyo, Japan) at the P2 position (left side of the 10th rib and 6 cm lateral to the spine) during each weighing period. Piglets were

weighed postfarrowing and at d 7, 14, and 21 of the lactation period. Mature milk samples were collected at 1000 h, 2 h after feeding, by manual extraction after thorough cleaning of the udder with water and an intramuscular injection of oxytocin (20 IU; Phoenix Pharmaceutical Inc., St. Joseph, MO). Milk samples were collected from all functional teats of all sows approximately 30 min after the piglets were separated from the dam on d 7 and 21 of lactation.

Blood samples were collected from the sows at 1000 h, 2 h after feeding, via jugular venipuncture by using heparinized tubes (Becton-Dickinson Vacutainer Systems, Rutherford, NJ) on d 7 and 21 of lactation. Blood samples were centrifuged at $2,000 \times g$ for 15 min. Plasma was separated by transfer pipettes into 1.5-mL microcentrifuge tubes (National Scientific, San Rafael, CA) and stored at -20°C until further AA, insulin, and urea analyses. All litters were weaned and the sows were returned to individual gestation crates at d 21 of lactation. The days until return to estrus were also recorded.

Chemical Analyses

Plasma samples (1 mL) were deproteinized with an equal volume of 1.5 M HClO_4 and neutralized with 0.5 mL of 2 M K_2CO_3 . The extracts were analyzed for urea concentrations by using a colorimetric method that involved a reaction with phenol and hypochlorite (Wu and Knabe, 1994). For analysis of all milk AA except for Trp, 0.2 mL of whole milk was hydrolyzed in 6 mL of 6 N HCl at 110°C for 24 h under N_2 (Wu and Knabe, 1994). For analysis of Trp, milk samples (0.2 mL) were hydrolyzed in 6 mL of 4.2 M NaOH plus 0.1 mL of thiodyglycol (25% aqueous solution, an antioxidant) as described by Wu et al. (1999). Amino acids in plasma and milk hydrolysates were analyzed by HPLC methods involving precolumn derivatization with *o*-phthalaldehyde (Wu et al., 1997). Amino acid standards and other chemicals were obtained from Sigma Chemical Company (St. Louis, MO). An enzyme immunoassay was used for the quantification of plasma insulin concentrations according to the manufacturer's instructions (Porcine insulin ELISA kit, Mercodia Inc., Winston Salem, NC). The detection limit was $0.01 \mu\text{g/L}$, and the coefficient of variation was 3.1% within assay and 1.5% between assay.

Statistical Analysis

Data were analyzed by using the MIXED procedure (SAS Inst. Inc., Cary, NC) for a factorial arrangement with a randomized complete block design. Sow was considered as the experimental unit. Separation of means was done by using the PDIF option of SAS. Probability values less than 0.05 were considered statistically significant, and values between 0.05 and 0.07 were considered as trends.

RESULTS

Piglet Performance

Litter size both after cross-fostering and at d 7, 14, and 21 did not differ among treatment groups. Litter sizes at d 0, 7, 14, and 21 of lactation were 10.9 ± 0.20 , 10.6 ± 0.20 , and 10.3 ± 0.19 (pooled means \pm SEM), respectively. Both gestation and lactation diets did not affect BW, BF thickness, ADFI, or days until return to estrus (Table 2). Main effects of gestation and gestation \times lactation interactions were not significant for all piglet performance data during lactation. Piglet BW at the initiation of cross-fostering did not differ among treatment groups. However, BW of piglets from sows fed the Arg-supplemented diets during lactation were greater ($P < 0.05$) at d 7 (2.62 ± 0.11 vs. 2.44 ± 0.11 kg), 14 (4.18 ± 0.20 vs. 3.86 ± 0.21 kg), and 21 (5.76 ± 0.22 vs. 5.36 ± 0.23 kg) of lactation compared with piglets from control-fed sows. Weight gains of piglets from sows fed the Arg-supplemented diet during lactation were greater between d 0 and 7 (1.26 ± 0.09 vs. 1.00 ± 0.09 kg; $P < 0.01$) and between d 0 and 21 (4.34 ± 0.21 vs. 3.92 ± 0.22 kg; $P < 0.05$) compared with piglets from the control-fed sows. However, there was no difference in piglet BW gain during either d 7 to 14 or d 14 to 21 of lactation.

Plasma Urea Concentrations in Sows

No significant gestation \times lactation interaction effect on plasma urea concentrations in sows was noted among the different treatment groups on d 7 or 21 of lactation (Table 3). There was a trend ($P = 0.071$) for sows fed the Arg-supplemented diet during gestation to have decreased plasma concentrations of urea (4.6 ± 0.07 vs. 4.8 ± 0.06 mmol/L) at d 7 of lactation compared with sows fed the control diets. In addition, sows fed Arg-supplemented diets during the lactation period had decreased plasma concentrations of urea (4.5 ± 0.08 vs. 4.8 ± 0.07 mmol/L; $P < 0.05$) at 7 d of lactation compared with sows fed the control diet.

Plasma AA Concentrations in Sows

Plasma concentrations of AA in first-parity sows at d 7 of lactation are summarized in Table 4. No significant gestation effect among treatment groups was observed for any AA measured. Except for Met, no gestation \times lactation diet interaction effect was noted for all other AA. Arginine supplementation to sows during the lactation period resulted in greater ($P < 0.01$) plasma concentrations of Pro, Gly, Arg, and ornithine compared with the control sows. However, plasma concentrations of Ser, Gln, His, citrulline, and Ala were decreased for sows fed Arg-supplemented diets during lactation when compared with sows fed isonitrogenous control diets. A gestation \times lactation diet interaction effect was noted for Met at 7 d of lactation ($P < 0.05$). There were no differences in plasma concentrations of

Table 2. Lactation performance of first-parity sows fed diets with or without supplemental 1% L-Arg·HCl

Item	Treatment ¹				SEM	P-value		
	Control gestation diet		Arg gestation diet			Gestation	Lactation	G × L ²
	Control lactation diet	Arg lactation diet	Control lactation diet	Arg lactation diet				
Observations, n	8	9	10	11				
Piglet								
BW, kg								
0	1.43	1.43	1.45	1.42	0.025	0.895	0.749	0.753
7	2.42	2.62	2.48	2.80	0.049	0.279	0.011	0.678
14	3.81	4.14	3.91	4.22	0.069	0.521	0.023	0.955
21	5.26	5.66	5.46	5.86	0.089	0.244	0.024	0.987
BW gain, g/d								
0 to 7 d	140.0	170.0	147.1	191.4	0.046	0.234	0.004	0.576
7 to 14 d	202.9	220.0	202.9	208.6	0.036	0.588	0.290	0.589
14 to 21 d	205.7	217.1	221.4	234.3	0.050	0.264	0.409	0.963
Overall	182.9	202.4	191.0	211.4	0.093	0.326	0.024	0.955
Sow								
BW, kg								
After farrowing	180.4	178.6	177.7	181.1	1.931	0.971	0.845	0.523
7 d	177.4	175.0	174.0	176.2	1.750	0.767	0.985	0.533
14 d	174.7	171.7	174.1	173.9	1.661	0.820	0.640	0.688
21 d	168.5	167.9	164.5	168.7	1.886	0.684	0.654	0.547
BW loss, kg	12.1	11.0	13.3	12.6	2.064	0.748	0.835	0.957
Backfat, mm								
After farrowing	15.4	15.3	15.5	15.3	0.186	0.934	0.732	0.813
7 d	13.1	13.1	13.1	13.1	0.209	0.953	0.987	0.996
14 d	11.5	11.1	11.7	11.6	0.219	0.429	0.621	0.722
21 d	10.9	10.2	10.8	10.5	0.227	0.793	0.342	0.675
Backfat loss, mm	4.5	5.1	4.7	4.7	0.201	0.826	0.448	0.487
ADFI, kg	6.1	6.0	5.9	6.0	0.114	0.906	0.997	0.715
Return to estrus, d	4.9	4.9	4.8	4.9	0.093	0.889	0.756	0.809

¹Gestation diets were fed at 2 kg/d in 2 separate meals (0700 and 1800 h); lactation diets were fed ad libitum up to weaning at 21 d. The Arg diets were supplemented with 1% L-Arg·HCl, and the control diets were supplemented with 1.7% L-Ala. The number of piglets per sow ranged from 9 to 13 piglets but was equalized within BW groups (blocks).

²G × L = gestation × lactation interaction effect.

other AA between control and Arg-supplemented sows. Similar results were obtained for plasma concentrations of AA in control and Arg-supplemented sows at d 21 of lactation (data not shown).

Concentrations of Total AA in Milk

Day 7 of Lactation. Concentrations of total AA (both protein-bound and free) in the milk of first-parity sows

Table 3. Plasma urea concentrations in first-parity sows fed diets with or without supplemental 1% L-Arg·HCl

Item	Treatment ¹				SEM	<i>P</i> -value		
	Control gestation diet		Arg gestation diet			Gestation	Lactation	G × L ²
	Control	Arg	Control	Arg				
	lactation diet	lactation diet	lactation diet	lactation diet				
Observations, n	8	9	10	11				
Lactation, d	mmol/L							
7	4.9	4.6	4.7	4.5	0.051	0.071	0.024	0.671
21	4.6	4.5	4.7	4.6	0.056	0.351	0.218	0.434

¹Gestation diets were fed at 2 kg/d in 2 equally sized meals (0700 and 1800 h); lactation diets were fed ad libitum up to weaning at 21 d. The Arg diets were supplemented with 1% L-Arg·HCl, and the control diets were supplemented with 1.7% L-Ala.

²G × L = gestation × lactation interaction effect.

Table 4. Plasma AA concentrations in first-parity sows fed diets with or without supplemental 1% L-Arg·HCl

Item	Treatment ¹				SEM	<i>P</i> -value		
	Control gestation diet		Arg gestation diet			Gestation	Lactation	G × L ²
	Control	Arg	Control	Arg				
	lactation diet	lactation diet	lactation diet	lactation diet				
Observations, n	8	9	10	11				
AA	μmol/L							
Ala	882	451	778	504	61.84	0.802	0.002	0.442
Asn	109	80	77	88	7.92	0.468	0.555	0.233
Asp	31	25	26	30	1.96	0.880	0.872	0.197
Arg	178	325	140	361	27.68	0.981	<0.001	0.321
b-Ala	45	44	49	49	1.45	0.162	0.942	0.940
Cit	67	52	69	56	3.27	0.607	0.032	0.878
Cys	298	301	304	310	4.53	0.478	0.625	0.886
Glu	244	165	177	128	24.09	0.301	0.204	0.757
Gln	623	466	554	451	22.39	0.231	0.001	0.432
Gly	595	1,356	1,106	1,489	106.14	0.517	0.002	0.235
His	122	74	110	77	5.64	0.505	<0.001	0.264
Ile	110	108	104	108	4.64	0.750	0.937	0.807
Leu	168	162	151	153	6.82	0.486	0.756	0.928
Lys	143	118	93	133	12.31	0.488	0.757	0.215
Met	37	28	28	29	1.33	0.100	0.113	0.022
Orn	93	159	75	137	11.61	0.302	0.003	0.910
Phe	77	73	68	74	2.92	0.534	0.834	0.481
Pro	308	527	303	549	27.60	0.585	<0.001	0.391
Ser	163	125	149	127	5.31	0.453	0.002	0.285
Tau	39	28	35	32	2.08	0.999	0.085	0.331
Thr	135	104	123	121	5.15	0.802	0.093	0.147
Try	54	50	48	47	3.17	0.550	0.737	0.786
Tyr	110	112	101	113	4.98	0.734	0.545	0.626
Val	195	183	174	191	11.75	0.798	0.900	0.577

¹Gestation diets were fed at 2 kg/d in 2 equally sized meals (0700 and 1800 h); lactation diets were fed ad libitum up to weaning at 21 d. The Arg diets were supplemented with 1% L-Arg·HCl, and the control diets were supplemented with 1.7% L-Ala. Blood samples were obtained 2 h after feeding in the morning.

²G × L = gestation × lactation interaction effect.

at 7 d of lactation are summarized in Table 5. No main effect of gestation or no gestation × lactation interaction effects were noted for all AA measured. There was a trend ($P < 0.09$) for concentrations of Ala, Val, Ile, Pro, Cys, and Trp in milk to be greater for sows fed Arg-supplemented diets compared with the control-fed sows. However, concentrations of Glu, Ser, Gly, Thr, Tyr, and Phe in milk were greater ($P < 0.05$) for sows fed the Arg-supplemented diets in comparison with the control-fed sows. There were no differences in concentrations of other AA in milk between control and Arg-supplemented sows. Total AA content in milk was greater ($P < 0.05$) for sows fed the Arg-supplemented diets compared with the control-fed sows (Table 5).

Day 21 of Lactation. Concentrations of total AA in the sow's milk at 21 d of lactation are summarized in Table 6. No main effects of gestation or no gestation × lactation interactions were noted for all AA measured. There was a trend ($P < 0.10$) for concentrations of Ser, Thr, Tyr, Met, Phe, Leu, and Pro in milk to be greater for sows fed Arg-supplemented diets, compared with the control-fed group. Concentrations of both Asp and Gly in milk were greater ($P < 0.05$) for sows fed the

Arg-supplemented diets compared with the control-fed sows. There were no differences in concentrations of other AA or total AA in milk between control and Arg-supplemented sows.

Plasma Insulin Concentrations in Sows

No significant gestation effect or no gestation × lactation interaction effect on maternal plasma insulin concentrations was noted among the different treatment groups at d 7 or 21 d of lactation (Table 7). However, plasma insulin concentration was greater ($P < 0.05$) at both d 7 and 21 of gestation in sows fed the Arg-supplemented diets, compared with sows fed the control diets (Table 7).

DISCUSSION

Results from the current study demonstrate that supplementing Arg to the diet of sows during the entire lactation period increased concentrations of total AA in milk and improved piglet growth performance. These

Table 5. Concentrations of total AA, on d 7 of lactation, in milk of first-parity lactating sows fed diets with or without supplemental 1% L-Arg·HCl

Item	Treatment ¹				SEM	<i>P</i> -value		
	Control gestation diet		Arg gestation diet			Gestation	Lactation	G × L ²
	Control	Arg	Control	Arg				
	lactation diet	lactation diet	lactation diet	lactation diet				
Observations, n	8	9	10	11				
AA	mmol/L							
Ala	23.10	25.30	24.10	26.20	0.550	0.398	0.056	0.989
Asp	40.00	42.80	41.30	44.40	0.848	0.433	0.103	0.947
Arg	8.40	9.20	8.70	9.40	0.203	0.569	0.110	0.944
Cys	6.20	6.60	6.40	6.80	0.114	0.349	0.065	0.948
Glu	65.40	69.20	66.60	71.80	1.010	0.359	0.034	0.714
Gly	15.30	16.80	15.50	17.80	0.399	0.489	0.018	0.651
His	6.20	6.60	6.40	6.80	0.129	0.391	0.112	0.833
Ile	18.20	19.90	18.80	20.60	0.453	0.494	0.060	0.976
Leu	35.50	38.20	35.90	38.70	0.847	0.831	0.114	0.982
Lys	29.40	31.60	30.50	32.60	0.656	0.431	0.117	0.946
Met	7.10	7.60	7.20	7.80	0.157	0.552	0.100	0.764
Phe	13.10	14.40	13.30	15.30	0.312	0.376	0.007	0.532
Pro	51.00	54.10	52.30	55.60	0.901	0.423	0.081	0.952
Ser	23.60	26.10	25.10	27.60	0.604	0.198	0.039	0.982
Thr	20.10	22.00	20.60	23.30	0.471	0.335	0.014	0.672
Try	3.40	3.60	3.40	3.70	0.070	0.585	0.056	0.520
Tyr	11.10	12.80	11.60	13.60	0.332	0.338	0.006	0.838
Val	22.60	24.20	23.20	25.50	0.489	0.357	0.052	0.720
Total protein, g/L	39.97	43.09	41.08	44.75	0.759	0.371	0.030	0.856

¹Gestation diets were fed at 2 kg/d in 2 equal-size meals (0700 and 1800 h); lactation diets were fed ad libitum up to weaning at 21 d. The Arg diets were supplemented with 1% L-Arg·HCl, control diets were supplemented with 1.7% L-Ala.

²G × L = gestation × lactation interaction effect.

findings provide a new strategy for the nutritional management of sow-reared neonates.

Litter weight gain is known to be correlated with milk production or nutrient concentrations in milk (Noblet and Etienne, 1987; King et al., 1993). Increased piglet or litter weight gain in Arg-supplemented sows may be indicative of increased milk production or increased nutrient concentrations in milk. Results of the current study indicate that voluntary feed intake and BW changes of sows were not affected by dietary Arg supplementation (Table 2), suggesting that increased concentrations of total AA in milk were not due to alterations in dietary protein intake or whole-body protein mobilization. On the basis of reduced levels of urea in plasma, Arg supplementation appears to enhance the efficiency of dietary protein utilization for milk protein synthesis. By increasing the synthesis of nitric oxide (a major vasodilator) in the endothelial cells of blood vessels (Moncada et al., 1989; Wu and Meininger, 2000), dietary Arg supplementation can enhance blood flow and nutrient supply to the mammary gland for milk protein, resulting in improved BW gain of suckling piglets. The increased concentrations of total AA in milk were associated with increased BW gain of piglets during the first week of lactation, which affected the overall improvement of piglet growth performance during the entire lactation period.

On average, piglets from Arg-supplemented sows gained 20 g more BW per day, or 420 g more during the 21-d lactation period, compared with the piglets from sows in the control groups (Table 2). Considering that body composition in neonatal pigs is approximately 25% DM and 12.5% protein (McPherson et al., 2004), 420 g of BW gain is translated into 50 g of protein gain in 3 wk for a piglet. As shown in Table 5, the increase in concentrations of total AA in the milk of Arg-supplemented sows is approximately 3.4 g/L. Considering that a piglet with 200 g of daily BW gain obtains 0.78 L of milk per day (Wu et al. 2004), the Arg treatment would provide 2.65 g of additional protein to the piglet per day, or 56 g during the 21-d lactation period. Because the digestibility of milk protein is high (95 to 100%) in neonatal pigs (Lin et al., 2006), the intake of an additional 56 g of protein from milk is sufficient to support the gain of an additional 50 g of protein in each piglet during a 21-d lactation period.

Furthermore, mammary blood flow and substrate concentrations in blood are major factors that determine substrate availability for milk synthesis (Davis and Collier, 1985) and therefore nutrient delivery to the neonate. Arginine is the physiological precursor for the synthesis of nitric oxide, the endothelium-derived relaxing factor (Wu and Meininger, 2000) and a key angiogenic factor (Meininger and Wu, 2002). Increasing

Table 6. Concentrations of total AA, on d 21 of lactation, in milk of first-parity lactating sows fed diets with or without supplemental 1% L-Arg·HCl

Item	Treatment ¹				SEM	<i>P</i> -value		
	Control gestation diet		Arg gestation diet			Gestation	Lactation	G × L ²
	Control	Arg	Control	Arg				
	lactation diet	lactation diet	lactation diet	lactation diet				
Observations, n	8	9	10	11				
AA	mmol/L							
Ala	20.7	22.00	20.60	23.10	0.560	0.679	0.102	0.598
Asp	38.90	41.10	37.90	43.60	1.000	0.695	0.049	0.372
Arg	8.40	8.70	8.30	9.00	0.180	0.811	0.185	0.637
Cys	6.00	6.30	6.00	6.50	0.130	0.747	0.186	0.753
Glu	64.40	67.10	63.60	70.04	1.590	0.704	0.148	0.531
Gly	14.20	15.30	14.20	16.20	0.360	0.572	0.039	0.569
His	5.90	6.00	6.00	6.50	0.140	0.284	0.215	0.418
Ile	16.80	17.90	16.70	19.00	0.500	0.615	0.110	0.576
Leu	33.70	35.90	33.90	38.30	0.990	0.495	0.097	0.568
Lys	27.30	28.90	27.50	30.60	0.810	0.560	0.143	0.617
Met	6.90	7.30	6.90	7.50	0.130	0.602	0.069	0.672
Phe	11.80	12.40	11.14	13.20	0.340	0.745	0.075	0.349
Pro	49.10	52.40	49.30	50.43	1.070	0.624	0.052	0.685
Ser	22.20	23.50	21.90	25.00	0.550	0.562	0.057	0.429
Thr	18.4	19.50	18.20	20.60	0.470	0.630	0.077	0.511
Try	3.30	3.40	3.20	3.50	0.070	0.786	0.150	0.641
Tyr	10.30	10.90	10.10	11.80	0.290	0.541	0.069	0.407
Val	20.80	21.70	20.50	23.30	0.590	0.550	0.101	0.439
Total protein, g/L	37.93	39.15	38.56	42.29	0.882	0.290	0.166	0.482

¹Gestation diets were fed at 2 kg/d in 2 equally sized meals (0700 and 1800 h); lactation diets were fed ad libitum up to weaning at 21 d. The Arg diets were supplemented with 1% L-Arg·HCl, and the control diets were supplemented with 1.7% L-Ala.

²G × L = gestation × lactation interaction effect.

nitric oxide availability has been reported to increase mammary blood flow rapidly in ruminants (Lacasse et al., 1996; Lacasse and Prosser, 2003). Interestingly, a short-term increase in nitric oxide provision within several hours may not lead to increased milk production (Prosser et al., 1996; Lacasse and Prosser, 2003), possibly because of a lack of increase in the number of secreting cells and the synthesis of proteins, fat, and lactose.

As noted above, rapidly growing piglets have a high requirement for Arg. However, previous studies have clearly demonstrated that limited Arg availability from sow's milk (Wu and Knabe, 1994; Wu et al., 2004) and the limited capability for endogenous Arg synthesis (Wu and Knabe, 1995) are both major obstacles in realizing the maximum growth potential of sow-reared piglets (Kim and Wu, 2004; Wu et al., 2004; Kim et al., 2007). The marked decrease in the availability of Arg coincides with the period when submaximal growth in piglets occurs (Boyd et al., 1995; Flynn et al., 2000; Kim and Wu, 2004). In support of this view, Kim and Wu (2004) demonstrated that dietary Arg supplementation dose-dependently enhanced the growth performance of artificially reared piglets.

Trottier et al. (1997) also reported that Arg uptake by the mammary gland is much greater than milk Arg output, which reflects the high capacity of the porcine mammary gland to catabolize Arg (O'Quinn et al.,

2002). Thus, Arg supplementation did not result in a substantially greater Arg concentration in sow's milk. However, an increase in the volume of milk consumed by piglets (Kirchgessner et al., 1991) would translate into an increase in the provision of Arg and other nutrients to the neonates to support their growth. This was clearly observed for suckling piglets on d 0 to 7 (Table 2). However, there was a lack of a significant increase in piglet BW gain during wk 2 and 3 in response to Arg supplementation (Table 2). The underlying reasons are not known at present, but may be related to unaltered concentrations of total AA in milk after the first week of lactation (Table 6).

As expected, Ala-supplemented sows had greater concentrations of Ala in plasma compared with Arg-supplemented sows. However, an interesting observation from the current study is that dietary Arg supplementation to lactating sows decreased plasma concentrations of Ser, Glu, His, and Thr at d 7 of lactation. It is possible that there was an increase in the utilization of these AA by the mammary gland for the synthesis of proteins, peptides, and other milk components. In support of this suggestion, we showed that concentrations of total AA (primarily protein) in milk increased at d 7 of lactation in Arg-supplemented sows. We surmise that Arg supplementation to gestating sows may have stimulated mammary growth (including vascular growth), thereby

Table 7. Plasma insulin concentrations in first-parity sows fed diets with or without supplemental 1% L-Arg·HCl

Item	Treatment ¹				SEM	<i>P</i> -value		
	Control gestation diet		Arg gestation diet			Gestation	Lactation	G × L ²
	Control lactation diet	Arg lactation diet	Control lactation diet	Arg lactation diet				
	8	9	10	11				
Observations, n	8	9	10	11				
Lactation, d	μg/L							
7	2.19	3.25	2.25	3.00	0.14	0.735	0.002	0.565
21	3.20	3.73	3.29	3.86	0.10	0.621	0.010	0.974

¹Gestation diets were fed at 2 kg/d in 2 equally sized meals (0700 and 1800 h); lactation diets were fed ad libitum up to weaning at 21 d. The Arg diets were supplemented with 1% L-Arg·HCl, and the control diets were supplemented with 1.7% L-Ala.

²G × L = gestation × lactation interaction effects.

promoting blood flow and AA uptake by the mammary gland to increase milk protein synthesis during the lactation period. This suggestion is consistent with the finding that the majority of growth in these tissues occurs during the later parts of gestation (Kim et al., 1999). Tucker (1966) and Kim et al. (2000) showed that total DNA content is an indicator of the number of mammary cells and is highly correlated with litter weight gain in pigs and rodents. Measuring DNA content in mammary tissue would provide a useful indicator in both control and Arg-supplemented sows; however, mammary DNA was not measured in this study.

The size of suckling piglets is positively correlated with the mass of mammary gland suckled (Nielsen and Sorensen, 1998; Kim et al., 2000). Consistent with this observation, we observed that piglets suckling from Arg-supplemented sows were heavier throughout lactation, with an increase in BW gain. Furthermore, the secretagogue effects of Arg on anabolic hormones, such as insulin (Floyd et al., 1966; Kim and Wu, 2004; Laspiur et al., 2006), may also play a role in the increased uptake of AA by the mammary gland (Laarveld et al., 1981). Previous reports from studies with other species have shown that the mammary gland becomes highly sensitive to insulin during lactation (Burnol et al., 1990). Thus, an increase in concentrations of plasma insulin and its sensitivity in Arg-supplemented lactating sows may stimulate the utilization of AA by the mammary gland to produce proteins. In dairy cows subjected to an insulin clamp, there was an increase in both mammary blood flow and the efficiency of extraction of blood AA by the mammary gland (Mackle et al., 2000). The increase in insulin secretion during lactation may also explain, in part, the decreased plasma concentrations of several AA measured (Fukagawa et al., 1986). These results suggest that supplementing Arg to the diets of lactating sows may increase the uptake of substrates (e.g., AA) by the porcine mammary gland for milk protein synthesis. Although this effect was more apparent during the initial period of lactation, the increased piglet performance during the first week of life

translated to an overall improvement in piglet performance.

Urea is the major end product of AA oxidation in mammals (Meijer et al., 1990). Previous studies suggested that plasma urea concentrations in lactating sows may be an indicator of efficiency of whole-body nitrogen utilization (Coma et al., 1995). There were no differences in feed intake among all groups of lactating sows (Table 2). Thus, a reduction in plasma urea levels in Arg-supplemented sows may reflect an increase in the use of dietary AA for tissue or milk protein synthesis, as previously reported for Arg-supplemented gestating gilts (Mateo et al., 2007), lactating sows (Laspiur and Trottier, 2001), and neonatal pigs (Kim and Wu, 2004). Interestingly, no differences in plasma urea concentration among sows were observed at d 21 of lactation, which agrees with the observation that piglet BW gain in wk 2 and 3 was not affected by Arg supplementation of the sow's diet (Table 2).

In summary, supplementing dietary Arg to lactating sows enhanced the growth performance of suckling piglets. The increased litter weight gain was associated with increased concentrations of total AA in milk at d 7 of lactation. We propose that the Arg treatment may increase mammary blood flow and extraction of AA during lactation. However, further studies are necessary to test this new hypothesis.

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